AUTO-EXTINCTION OF ENGINEERED TIMBER AS A DESIGN METHODOLOGY

WCTE 2016
World Conference on Timber Engineering
August 22-25, 2016 | Vienna, Austria

AUTO-EXTINCTION OF ENGINEERED TIMBER AS A DESIGN METHODOLOGY

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ABSTRACT: Engineered timber products such as cross-laminated timber (CLT) are gaining popularity with designers due to attractive aesthetic, sustainability, and constructability credentials. The fire behaviour of such materials is a key requirement for buildings formed predominantly of exposed, structural timber elements. Whilst design guidance focuses on the residual structural capacity of timber elements exposed to a 'standard fire', the fundamental characteristics of CLT's performance in fire, such as ignition, flame spread, delamination, and extinction are not currently considered. This paper focuses on the issues relating to increased fuel load due to a combustible building material itself. Whilst an increasingly common protection solution to this conundrum is to fully encapsulate the timber elements, there is limited supporting test data on this approach. In order to enable the construction industry's interest in this construction material, practical and robust solutions are required.

In this paper therefore, the concept of auto-extinction – a phenomenon by which a timber sample will cease flaming when the net heat flux to the sample drops below a critical value – is explored experimentally and related to firepoint theory. A series of c.100 small scale tests in a Fire Propagation Apparatus (FPA) have been carried out to quantify the conditions under which flaming extinction occurs. Critical mass loss rate at extinction is shown to occur at a mass flux of 3.5g/m^{2}s or a temperature gradient of 28K/mm at the charline. External heat flux and airflow were not found to affect the critical mass loss rate at the range tested. This approach is then compared with a compartment fire with multiple exposed timber surfaces. With further testing and refinement, this method may be applied in design, enabling architects' visions of exposed, structural timber to be safely realised.

KEYWORDS: Cross Laminated Timber, CLT, Pyrolysis, Combustion, Extinction, Design

1 INTRODUCTION & BACKGROUND

Overcoming the uncertainty associated with the performance of engineered timber products in the event of a fire is a key step in enabling the robust application of these products in real building design and construction. The majority of existing research, and traditional design guidance on the fire performance of timber focusses on determining effective charring rates and directly relating these to a 'standardised' fire resistance rating. Regardless all approaches to date, primarily explore the material response rather than the system response. If engineered timber is to realise its full architectural potential of forming exposed, structural wall and floor slabs, then its fire behaviour in such scenarios must be properly understood from a fundamental scientific perspective, particularly where exposed engineered timber is a design aspiration.

In a system with multiple exposed structural timber wall and floor slabs, a fire in the compartment will result in the ignition of the exposed timber. After the compartment fire load has burnt out, these surfaces may continue to burn as the heat produced by the burning of each surface will radiate to the others. This radiative exchange can be estimated using configuration factors and surface temperatures. If this heat flux is less than the critical heat flux for sustained flaming, then auto-extinction of the exposed timber surfaces, should occur (i.e. the timber will cease burning). Otherwise flaming would continue potentially resulting in collapse in the absence of fire service intervention.

In order to treat the fire response of exposed engineered timber as a design parameter, knowledge of the conditions under which auto-extinction occurs must be obtained, and the governing parameters. This will enable a change in design guidance for engineered timber.

This paper presents experimental data examining these conditions, and introduces a design methodology for use in practice.

1.1 COMBUSTION OF TIMBER

The response of timber to fire is a complex phenomenon, with many different processes occurring simultaneously

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within the material. Four main stages can be identified as a timber specimen is heated by a fire: (1) dehydration, (2) pyrolysis, (3) combustion, (4) flameout.
Initially as timber is heated, the moisture will begin to evaporate, acting as a heat sink and slowing down the temperature rise of the surrounding timber [1] – most of this moisture escapes from the surface [2], resulting in a reduction of moisture content, which in turn increases the pyrolysis rate of the timber [3].
In order to for flaming combustion to occur, the constituent polymers of timber (cellulose, hemicellulose, and lignin) must first be thermally decomposed (pyrolysed) typically producing inert and combustible vapours, liquid tars, a solid carbonaceous char (which is typically around 20% the density of virgin wood [4]) and an inorganic ash.
To create a self-sustaining reaction, the combustion of these pyrolysis products must feedback sufficient heat to continue the production of volatiles [5]. This can occur before dehydration is completed if the heating rate is fast enough, but will be faster after the sample has dried. The complexity of this process arises due to the chemistry of the pyrolysis processes (charring) [6] and inherent material variability [2].
At temperatures below 200°C, pyrolysis occurs slowly [7], mostly producing inert gases. Although significant pyrolysis does not occur at these temperatures, and flaming ignition will not take place, the glass transition temperature of water-saturated lignin can be as low as 60°C [8], leading to loss of bond strength between fibres. Glass transition of lignin has an important effect on the elastic modulus of timber and thus the overall structural behaviour. Lignin experiences further significant reduction of mechanical strength at temperatures around 100°C, showing that loss of mechanical strength can occur significantly before the onset of charring. Prolonged heating at these temperatures can result in significant charring without flaming ignition.

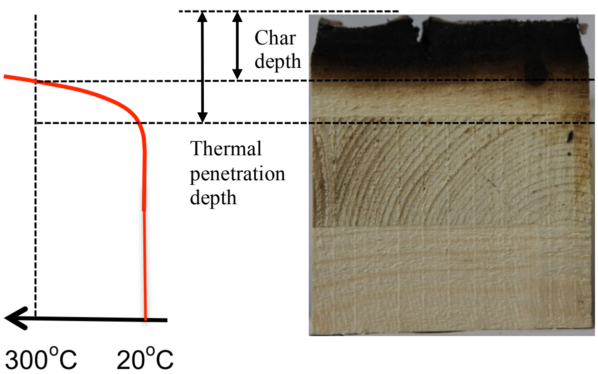

Figure 1: Charred timber sample showing temperature profile

Around 300°C, pyrolysis rates increase significantly [7], resulting in significant rates of pyrolyzate production, and a rapid formation of a rigid, carbonaceous char layer. As such, 300°C is commonly assumed to be the typical char formation temperature in design. The char layer, whilst having negligible structural strength, has a lower effective thermal conductivity than the virgin timber, and thus acts as protection for the underlying wood [9]. Therefore a specimen which has built up a significant char layer prior to ignition (for example through prolonged slow heating) will be more difficult to ignite. A typical charred timber specimen and a schematic of the temperature profile is shown in Figure 1.
Below the char layer, there is an additional heated layer of wood as illustrated in Figure 1 (thermal penetration depth), typically 35-40mm in depth [10]. This layer will continue to pyrolyse, releasing flammable gases and adding to the char layer, as long as there is sufficient heat available.
In the presence of oxygen, the pyrolysis products may undergo a rapid, exothermic reaction with oxygen – flaming combustion. The criteria required for this ignition are often defined as either the "critical heat flux", the lowest heat flux for which ignition will occur, or "critical surface temperature", the lowest *surface* temperature for which ignition will occur. In reality, these factors will vary significantly with environmental conditions (i.e. test setup, sample size and orientation [9, 11, 12]) and potentially even more complex in real building compartments. From a fundamental perspective, the necessary criteria for flaming ignition are a critical mass flux of volatiles, $\dot{m}''_{cr}$, [9] which can form a flammable mixture with the surrounding air and sufficient energy usually supplied as a pilot flame or spark. Drysdale [9] expresses this critical mass flux criterion through the energy balance presented in Equation 1:

$$(\phi \Delta H_c - L_v)\dot{m}''_{cr} + \dot{Q}''_e - \dot{Q}''_l > 0 \quad (1)$$

where ϕ is the fraction of the heat of combustion of the vapour transferred back to the surface, ΔH_c is the heat of combustion, L_v is the heat of gasification, $\dot{Q}''_e$ is the external heat flux, and $\dot{Q}''_l$ is the heat losses. This expression is a calculation of the net heat flux into the timber, which governs the quantity of volatiles released.
When timber is first ignited, the mass loss rate (hence pyrolysis rate) is high as the timber is pyrolysed and a char layer forms, the mass loss rate decreases to a lower, quasi-constant value once a char layer has formed [3].
If flaming combustion is not achieved, then the char layer itself may undergo smouldering combustion. This occurs when oxygen reacts directly with the exposed char layer, oxidising it and generating additional heat. This solid phase char oxidation is the main heat source in the majority of smouldering processes, and can lead to self-sustained smouldering combustion, which then has the potential to transition to flaming combustion [13].

1.2 RISK MANAGEMENT

The combustibility of timber must be explicitly considered in design, and the knowledge of its burning behaviour used to manage and satisfy fire safety objectives.
In a large compartment with exposed timber surfaces, gradual ignition of these surfaces may occur if the contents of the compartment (fuel load) burn and radiate heat to exposed timber surfaces. The amount of heat

radiated to these surfaces will decrease with distance from the fuel load.

In a smaller compartment, where flashover is likely to occur quickly, the presence of exposed timber surfaces have been shown to increases the rate of fire growth significantly reducing the time to flashover [14].

In both of these cases, the increased fire growth rates may pose a challenge to fulfilling life safety and structural integrity requirements. Additionally, there is the risk that the heat radiated between exposed surfaces is sufficient to keep the exposed surfaces burning even after burnout of the compartment fuel load. Through understanding these concepts from a fundamental, scientific perspective, the behaviour can be properly understood, and, rather than limiting design, can be incorporated into design to satisfy suitable performance criteria.

2 CRITICAL HEAT FLUX FOR SUSTAINED FLAMING

2.1 THEORY

To develop appropriate input data for a performance based design approach to engineered timber, an understanding of the fundamental phenomena that lead to extinction of the flame is required. As discussed, combustion is possible either through surface oxidation of the char layer, or by flaming ignition of the volatiles. It is well established that thermally thick wood will not burn on its own, but only when it is subjected to an additional, external heat flux [9], which can be supplied by a nearby burning object. Without this external heat flux, the heat losses will be larger than the heat available to drive pyrolysis and the flame will extinguish as the production of volatiles from the pyrolysis reaction decreases beyond a critical flux [15]. Once flaming ignition is achieved, significant char oxidation is unlikely because the combustion of pyrolysis gases consumes most of the oxygen, preventing significant flux reaching the char surface [7, 10]. As a result, the char layer will continue to increase in thickness [7], effectively insulating the virgin timber and resulting in a subsequent gradual decline in mass flux [16, 17].

It has been suggested that flame extinction and piloted ignition have the same critical conditions [9, 18], with both being dependent on 'firepoint' conditions [2]. It is worth noting however, that for a reactive material such as wood, the material itself will have undergone extensive physical and chemical changes between ignition and extinction, so the critical values at the two conditions may differ.

A flame will extinguish if the production of flammable vapours drops below a critical value, $\dot{m}''_{cr}$, as this will result in the air:fuel ratio adjacent to the solid surface dropping below the lower flammability limit. The pyrolysis rate per unit area can be expressed in terms of the imposed heat flux by Equation 2 [15], a rearrangement of Equation 1:

$$\dot{m}''_{cr} = \frac{\dot{Q}''_e + \dot{Q}''_f - \dot{Q}''_l}{L_v} \tag{2}$$

where $\dot{Q}''_f$ is the additional heat flux from the flames. Since gasification will occur for the virgin wood rather than the char, it is the net heat flux at the char:timber interface that is of interest. Applying Equation 2 at the char line and applying Fourier's law of conduction shows that the critical condition for flame extinction can be expressed either in terms of a critical mass loss rate or thermal gradient, expressed in Equation 3:

$$\left.\frac{dT}{dx}\right|_{x=x_c} = \frac{\dot{Q}''_e + \dot{Q}''_f - \dot{Q}''_l}{k_c} \tag{3}$$

where dT/dx is the temperature gradient at the charline, and k_c the thermal conductivity of char.

2.2 STATE OF THE ART

Rasbash et al. [19] present a method for quantifying the ignition and extinction conditions of a solid fuel in relation to the mass flow of volatiles released. A series of experiments was undertaken on PMMA samples subject to radiant heating to determine the effects of external heat flux, air flow on the surface and oxygen concentration on the critical mass flux. From about $12kW/m^2$ to $19kW/m^2$, the critical mass flux was found to increase with heat flux, from about $3.8g/m^2s$ to $5.2g/m^2s$; thereafter it became independent of external heat flux. This initial variation was attributed to flame behaviour varying with heat flux near the critical heat flux for ignition. The effects of airflow around the sample were also explored; an initial drop from around $5.3g/m^2s$ to $3.2g/m^2s$ was observed over the range of 0 to 30lpm of airflow, before rising again to around $5.0g/m^2s$ at 60lpm. Whilst these tests were carried out for a different material, the approach and influencing factors are relevant for timber design.

However, few researchers to date have explored the concept of flame extinction on timber surfaces. The earliest work was by Hottel [20], who tested small-scale vertical spruce samples under radiant heating and found that an incident heat flux of around $31.5kW/m^2$ was required to sustain a flame for more than ten minutes. Further tests in which the external heat flux was removed after ignition found that samples ignited at lower heat fluxes tended to take longer to extinguish, which was attributed to a greater heating time and thus shallower thermal gradient leading to lower heat losses at the char:wood interface.

Bamford et al. [1, 21] noted that for 230mm x 230mm deal panels of varying thicknesses from 9.5mm to 50.8mm heated by flames on two sides, after a given period of time, flaming will be self-sustaining upon removal of external heat sources. Panels heated only on one side, however, will not achieve self-sustained flaming if over 3mm thick. The time to reach sustained flaming was proportional to the square of sample thickness, with thicker samples taking longer. They found that the centreline temperature at the time of self-sustained heating was always around 200°C. They relate the conditions necessary for self-sustained flaming to the rate of volatile production, finding that a rate of 2.5g/m^{2}s was required for self-sustained burning.

Tests on 50mm thick oak and Columbian pine samples at heat fluxes ranging from 18 to 54kW/m^2 showed that samples subject to heat fluxes at or below 30kW/m^2 extinguished after around 2 to 7 minutes, reaching char depths of around 4 to 8mm. The samples subjected to 50kW/m^2 however, continued burning until the majority (84-100%) of the sample had charred.

Further tests [1] explored the combustion behaviour of two vertical wood panels set parallel and opposite each other. The thickness of the samples was found to have no effect. Square panels of length 229mm and rectangular panels 914mm x 381mm were tested. The smaller panels were found to cease undergoing sustained flaming for separations above 51mm, and for the larger panels, around 127mm. This corresponds to view factors of 0.66 and 0.65 respectively, suggesting that based on a similar flame temperature, this view factor corresponds to a critical energy balance for auto-extinction. The effect of airflow was also explored; as expected, a greater airflow resulted in longer times to ignition, but once ignited resulted in more complete combustion due to improved mixing conditions. For this reason, when these tests were repeated on vertical panels, the burning was much more vigorous.

More recently, Inghelbrecht [2] tested 100mm x 100mm CLT radiata pine (ρ=635kg/m^3) samples 72mm thick and hoop pine (ρ=540kg/m^3) samples 96mm thick, Gympie messmate (an Australian hardwood) glulam samples (ρ=823kg/m^3) 60mm thick, and solid hoop pine (ρ=560kg/m^3) samples 70mm thick in the vertical orientation in a cone calorimeter [22] under imposed heat fluxes of 25, 40, 60, and 80kW/m^2 perpendicular to the grain for exposure times of 10, 20, 30, and 60 minutes. Temperature was recorded using K-type thermocouples at depths of 5mm, 15mm, 25mm, 35mm, and 45mm from the heated surface; additionally mass loss was recorded throughout the tests. For the tests at 25kW/m^2, delamination (a phenomenon in which an outer lamella or part thereof detaches from the main timber section) occurred followed by flaming ignition. Upon removal of the external heat flux, the 80kW/m^2 samples (10 minutes exposure) extinguished after 2.5 minutes. The 25kW/m^2 samples (60 minutes exposure) had delayed self-extinguishment due to the delaminated first layer leaning against the rest of the sample serving as additional fuel. It was noted that a decrease in mass flux below a critical value will result in flameout.

Crielaard [23] tested twelve 100mm x 100mm x 50mm thick softwood CLT samples under a cone calorimeter at 75kW/m^2. Temperature was recorded by K-type thermocouples at various depths throughout the samples. When the samples had achieved a char depth of 20mm, the sample was moved under a second cone calorimeter, at a heat flux of 0 to 10kW/m^2, to determine the critical heat flux for smouldering extinction. This was found to be around 5 to 6kW/m^2. The final two experiments had an additional airflow of 0.5m/s and 1.0m/s over the sample respectively. Whilst the 0.5m/s airflow led to quicker extinction than with no airflow, an airflow of 1.0m/s led to sustained burning at 6kW/m^2. Thus the natural convective airflow within a compartment may have a significant effect on smouldering extinction; this may also apply to flaming extinction, as found by Rasbash et al. [19] for PMMA, and is thus an important aspect to consider.

3 EXPERIMENTAL INVESTIGATIONS

A series of experiments on 85mm x 85mm x 100mm thick softwood CLT samples of three uniform lamellae has been undertaken in the FM Global Fire Propagation Apparatus (FPA) to explore the conditions under which flame extinction occurs. Samples were wrapped in aluminium foil and two layers of ceramic paper to reduce heat losses through the sides and to promote one-dimensional heat transfer, thus simulating the heating of a slab. Sample mass and dimensions were recorded before and after each test, and during the test oxygen calorimetry was undertaken. Experiments were carried out with constant heat flux exposure and a two-phase exposure in which a "high" heat flux was applied for a prescribed time before reducing the heat flux to a "low" value to simulate heating from another burning CLT surface. Mass loss and temperature data (K-type thermocouples inserted at depths of 5mm, 10mm, 15mm, 20mm, 25mm, 30mm, 40mm, 50mm, and 60mm from the heated surface) were recorded. These measurements allow for an examination of critical mass loss rate and critical temperature gradient at extinction as identified earlier..

For constant heat flux exposure, the heat flux was varied from 14kW/m^2 to 35kW/m^2. Critical heat flux for piloted ignition in this setup was found to be between 13kW/m^2 and 14kW/m^2. Tests at or below 31kW/m^2 were found to eventually undergo flaming extinction, whereas tests at or above 32kW/m^2 were found to undergo sustained flaming, consistent with Hottel [20]. The tests that underwent flaming extinction were subject to a gradually declining mass loss rate, which upon reaching around 3.5g/m^{2}s, resulted in flaming extinction; slightly higher than that obtained by Bamford [21].

A typical mass loss profile is shown in Figure 2, in which the mass loss declines gradually before dropping below the critical mass loss rate. This critical mass loss rate for extinction was found to be independent of external heat flux.

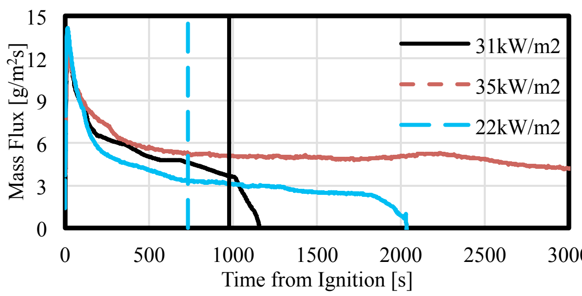

Figure 2: *Mass loss rate over time for samples exposed to a constant 22kW/m^2, 31kW/m^2, and 35kW/m^2, with flameout highlighted by vertical lines*

The two-phase tests had an initial heating phase of a constant 40kW/m^2 incident heat flux for 30 minutes, before dropping to a constant heat flux of 15kW/m^2 to 31kW/m^2. Most samples extinguished within two minutes after the reduction of heat flux, with the notable exception of the samples dropping to 31kW/m^2, of which two did not extinguish, and one extinguished only after an additional 37.5 minutes. This again suggests a critical heat flux for extinction of around 31kW/m^2 in this setup, with the value being independent of pre-heating. Mass loss rate at extinction was again around 3.5g/m^{2}s. Mass loss rate as a function of external heat flux at extinction is shown in Figure 3. Apart from clear outliers, it can be seen that mass loss is independent of heat flux, as found for PMMA by Rasbash et al.[19].

Tests in which temperature data were recorded found a critical temperature gradient at extinction of around 28K/mm at the char line. This was calculated by taking a linear temperature profile over the two thermocouples closest to the char line at extinction.

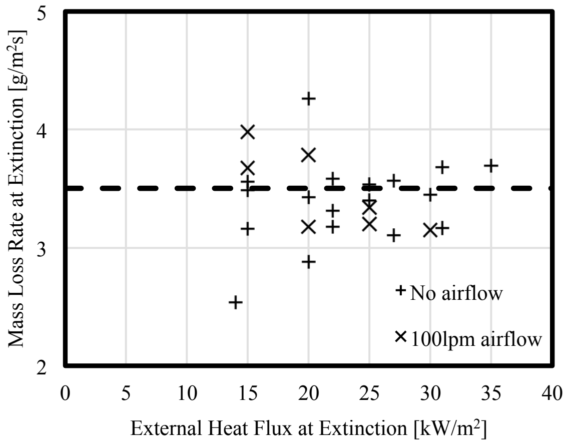

Figure 3: *Mass loss rate at extinction as a function of heat flux*

This experimentally determined critical mass loss rate and critical temperature gradient can therefore be used to estimate if auto-extinction occurs.

These values can also be used as a criteria in solving Equations 2 and 3. Of the other five parameters required, two of these are material parameters, L_v and k_c, which can be found from the literature: Tewarson and Pion [15] determined experimentally values for the heat of gasification, L_g, for various solids using differential scanning calorimetry. For timber, they found a heat of gasification of 1.82kJ/g. The heat of gasification includes the heat required to raise the solid to its pyrolysis temperature. Assuming a pyrolysis temperature of 300°C [16, 25] the heat of vaporisation can be calculated from Equation 4 [15]:

$$L_v = L_g - \int_{T_\infty}^{T_p} C_p dT \tag{4}$$

where C_p is the specific heat capacity of the timber (temperature dependent values taken from Eurocode 5 [26]), and T_∞ and T_p are the ambient and pyrolysis temperatures respectively. This gives a heat of vaporisation of 1.1kJ/g.

Temperature-dependent thermal conductivities are given in [26], and is around 0.10W/mK at 300°C. Equating this with the critical mass loss rate and heat of vaporisation gives a critical temperature gradient of 38K/mm – significantly higher than that obtained experimentally, but this may be in part due to linear interpolation over 5mm (the thermocouple spacing at the char:wood interface).

The remaining three parameters are now discussed in turn for the FPA experiments herein with an aim to extracting their use in design.

3.1 EXTERNAL HEAT FLUX, $\dot{Q}''_e$

The first parameter is the external heat flux, necessary to enable burning of a thermally thick wood sample [9], which serves as the control variable in the experimental investigations herein. In the case of the FPA experiments, this heat flux is simply the incident heat flux from the lamps, and this is known from calibration.

3.2 HEAT FLUX FROM FLAMES, $\dot{Q}''_f$

The second parameter is the heat flux from the flames, which can be estimated by Equation 5 [9]:

$$\dot{Q}''_f = \phi(\Delta H_{c,net} + L_v) \tag{5}$$

where ΔH_c has been experimentally determined herein as around 16.8kJ/g, consistent with literature values [9, 25]. Φ is the proportion of energy from the flame transferred back to the surface, and can be estimated through Equation 6 [19]:

$$\dot{m}''_{cr} = \frac{h_c}{C_{p,air}} ln\,(1 + \frac{m_{og}}{r}\phi) \tag{6}$$

where h_c is the convective heat transfer coefficient, $C_{p,air}$ the specific heat capacity of air, taken as 1.01kJ/kgK [27], m_{og} the mass concentration of oxygen in air (0.23 at ambient oxygen concentration), and r the stoichiometric ratio of oxygen to fuel (taken as 3.43 [19]). This gives ϕ = 0.15, and $\dot{Q}''_f$ = 2.6kW/m^2.

3.3 HEAT LOSSES, $\dot{Q}''_l$

The heat losses from an FPA sample come from four main sources – radiative losses, convective losses, and the heat absorbed by the char layer. In order to calculate these parameters, an estimate of surface temperature is required. This can be estimated based on thermocouple data in the char layer.

Radiative losses can be calculated simply using view factors and the surface temperature [28].

The convective heat transfer can then be estimated by calculating the Nusselt number for a horizontal plate [27], giving a convective heat transfer coefficient as defined in Equation 7:

$$h_c = 0.54 \sqrt[4]{\frac{g(T_s - T_\infty)}{LT_s \nu \alpha}} k \quad (7)$$

where L is the surface length, T_s is the surface temperature, ν is the kinematic viscosity of air, and α is the thermal diffusivity of air, giving a typical convective heat transfer coefficient of around 9W/m^{2}K.
Conductive heat losses are from the char:wood interface to the wood and can be calculated from Equation 8 [2]:

$$\dot{Q}''_{l,cond} = -k_{wood} \left. \frac{\partial T}{\partial x} \right|_{x=x_c} \quad (8)$$

where k_{wood} is the thermal conductivity of the wood at the char line. The heat absorbed by the char layer can be estimated by Equation 9:

$$\dot{Q}''_{abs,char} = \int_0^{x_c} \frac{C_p m}{At} dT \quad (9)$$

If char thickness is assumed to be constant over the time of interest, then this can be expressed by Equation 10:

$$\dot{Q}''_{abs,char} = \beta \int_{T_c}^{T_s} \rho C_p dT \quad (10)$$

Applying these values to a 15kW/m^2 case through Equation 2, assuming a surface temperature of 350°C from the thermocouple data at extinction gives a theoretical mass loss rate of 3.3g/m^{2}s, within 7% of the experimental value of 3.5g/m^{2}s. A sensitivity analysis revealed that the expression for radiative heat losses, in particular surface temperature, dominates. Changing the surface temperature ±50K results in a change in +69%/-84%. Thus for effective application of this approach in design, accurate calculations of surface temperature and/or heat losses are essential. Performing the same analysis with Equation 3 gives a critical temperature gradient of 35K/mm, 20% higher than that obtained experimentally. This error can be partially attributed to using a linear temperature gradient over 5mm, where in reality, the temperature profile beneath the char layer is highly non-linear [10], thus having temperature gradients decreasing with depth into the sample.

4 RELATION TO COMPARTMENT FIRE

This approach can then be applied to a full scale compartment fire scenario, to quantify and mitigate some of the risks present due to exposed timber surfaces.
Equation 2 presents the three main variables required to determine the mass loss rate – the external heat flux, $\dot{Q}''_e$, the additional heat flux from the flames, $\dot{Q}''_f$, and the heat losses, $\dot{Q}''_l$. Each of these can be calculated for a compartment fire scenario to determine whether auto-extinction will occur after burnout of the initial fuel load.

4.1 EXTERNAL HEAT FLUX, $\dot{Q}''_e$

In a system with multiple exposed timber surfaces, the heat produced by each burning surface will radiate heat to all the other surfaces. If the characteristic wall temperature is known, then the incident heat flux can be calculated from configuration factors through Equation 11:

$$\dot{Q}''_f = F_{ij} \varepsilon \sigma T_c^4 \quad (11)$$

where F_{ij} is the configuration factor, ε the surface emissivity, σ the Stefan-Boltzmann constant, and T_c the characteristic surface temperature, a weighted average of flame temperature and char temperature considering the prevalence of flames on the burning surface. As an example, the variation in dimensionless heat flux, $\dot{Q}''_f / \overline{\dot{Q}''_f}$ (where $\overline{\dot{Q}''_f}$ is the average heat flux over the surface) in the x- and y- directions is shown in Figure 4 for two equal and opposite surfaces.

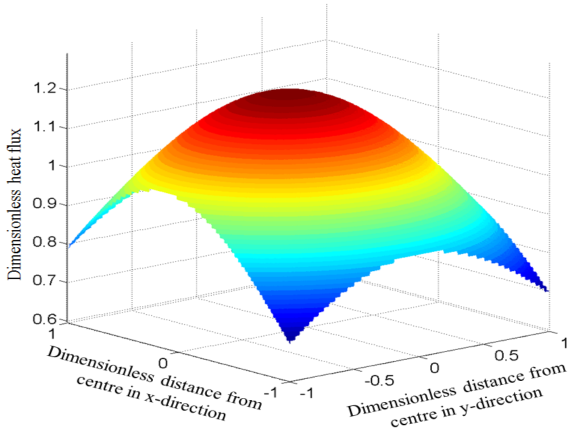

Figure 4: *Variation in dimensionless heat flux between two equal and opposite surfaces*

4.2 HEAT FLUX FROM FLAMES, $\dot{Q}''_f$

The heat flux from the flames can be calculated using Equation 5, as for the FPA tests. In a compartment, experimentally, h_c is around 10 to 40W/m^{2}K [2], with an average value of 25W/m^{2}K usually taken in design – significantly higher than that in the FPA. Additionally, due to the elevated gas temperatures, the specific heat of air will be higher, rising almost linearly to 1.189kJ/kgK at 1300K [27]. This puts ϕ in the range of 0.13 to 0.62, corresponding to a heat flux from the flames of 6.7±4.4kW/m^2.

4.3 HEAT LOSSES, $\dot{Q}''_l$

Heat losses in a compartment fire setting will be significantly different to a lab-scale setup. Due to the circulation of hot gases in a compartment, convective heat losses will be minimal.
Radiative heat losses to other non-timber surfaces may be significant, depending on the building material. As with the heat exchange between timber surfaces, this can

be estimated based on configuration factors and surface temperatures.
Conductive heat losses are likely to be significant, and can again be calculated from Equation 9.
Heat absorbed by the char layer can again be calculated by Equation 10.

5 APPLICATION IN DESIGN

Given further testing and refinement, the above methodology maybe used as a design methodology to determine if auto-extinction is likely to occur in a given scenario. A potential approach is highlighted in Table 1:

Table 1: *Proposed steps for incorporating auto-extinction into design methodology*

(1)	Determine time to burnout of compartment fuel load
(2)	Based on amount of exposed timber after burnout, calculate view factors and incident heat flux
(3)	Make an estimate of surface temperature based on heat transfer analysis/experimental data.
(4)	Estimate heat losses based on compartment geometry and surface temperatures
(5)	Solve Equation 2 to determine if mass loss rate is less than the critical value
(6)	Repeat for next timestep until: a. Auto-extinction occurs b. Pre-defined failure criteria are met c. A steady-state is achieved

It is necessary to perform these steps as a time-dependent analysis, as temperatures in the exposed timber surfaces will increase with time, resulting in an increased char layer and gradually declining mass fluxes, as with the FPA tests herein. Gradual reductions in heat release rate have also been observed in CLT compartment fires [14], highlighting that similar behaviour as observed here exists in the large-scale.
Three different outcomes are possible in this scenario (assuming no firefighter intervention): 1) auto-extinction occurs due to mass loss rate dropping below the critical value; 2) mass loss rate starts to decline, but loss of integrity or load-bearing capacity occurs before auto-extinction; 3) radiation between surfaces is sufficiently great that mass loss rate reaches a steady value and does not result in auto-extinction.
In the case of auto-extinction occurring, the compartment can be said to have survived the design fire given some additional considerations.

5.1 ADDITIONAL CONSIDERATIONS

Delamination is a phenomenon by which the fire-exposed lamella (or part thereof) detaches from the rest of the member. When the charred layer falls off, the layer beneath is suddenly exposed to the fire and it has been observed that this results in faster burning and pyrolysis until the char layer has been re-established [29]. This faster pyrolysis may result in re-ignition after auto-extinction has occurred [23]; thus it is vital to prevent delamination or mitigate its effects. Softening of the glue-line is acknowledged as a primary cause of delamination [29], although over what temperature range this occurs for different commonly-used adhesives is presently unknown. Additionally, the effects of structural loading and moisture migration on delamination (if any) are unknown. Detailed research into understanding and predicting when delamination occurs is necessary before this design methodology could be fully adopted.
The falling off of plasterboard attached to the engineered timber as a lining (e.g. for fire protection) will also affect the extinction behaviour, as it has been observed that when a timber surface is exposed due to the fall-off of plasterboard, the heat release rate significantly increases due to the involvement of the newly exposed timber surface, as expected [30]. As this additional surface is exposed, the fire dynamics will be affected and the re-radiation between the walls will significantly increase (by up to 300% if the system with two exposed surfaces increases to a system with five exposed surfaces) most likely to the extent that the critical conditions for auto-extinction are greatly exceeded. Thus not only must the conditions for auto-extinction detailed herein be met, but it must be demonstrated that the plasterboard (or other encapsulating system) on unexposed timber surfaces will remain in place until auto-extinction has occurred.
Smouldering is an additional concern which must be addressed to adopt this methodology. In similar tests to these FPA tests, Crielaard [23] found a critical heat flux for smouldering extinction of 5 to $6kW/m^2$ – substantially lower than the $31kW/m^2$ for flaming extinction. This would suggest that after flaming extinction has occurred, smouldering combustion may continue. Whilst smouldering extinction occurs much more slowly than flaming combustion, as can be seen in Figure 2 in the sharp decline in mass loss rate, the full effects must be understood and quantified.
Finally, the residual structural capacity of the structure post-flameout must be understood, to ensure flameout occurs before structural collapse.

6 CONCLUSIONS

From these data, it can be hypothesised that if the heat flux to an exposed timber element within a compartment is such that the mass loss rate will be less than $3.5g/m^2s$ and/or the temperature gradient at the charline less than 28K/mm, then auto-extinction will occur. Airflow was not found to have an effect on extinction conditions over the range tested. However, since this was a variable identified by Rasbash et al. [19] as effecting extinction, a wider range of airflow rates, and their effects on extinction, should be investigated.
Through modelling of the exposed timber surfaces in a compartment fire, an energy balance can be applied as described herein, and it can be predicted whether such a surface will undergo flaming extinction. If auto-extinction can be demonstrated, then this may be applied as an input as part of a new performance based design methodology.

Some further work is necessary to refine the approach outlined herein, as detailed in section 5.1. Namely, the effects of additional phenomena such as delamination, smouldering, plasterboard (or other applied solid protection material) integrity, and airflow conditions should be explored to produce a robust predictive model. All the above findings should be verified through large-scale compartment tests to ensure the methodology is applicable to real buildings and is valid for design.

ACKNOWLEDGEMENT

The authors gratefully acknowledge generous support from Arup, partly through EPSRC iCASE Studentship 14220013.

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